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30th November 1994

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1 Introduction

Although in principal many meteorological phenomena pose a threat to aviation, most transport aircraft have a significant "all-weather" capability. Two examples of "all-weather" capability are an anti-icing system or a flight control system which will mitigate the effects of turbulence on certain scales. Here transport aircraft typically means airliners carrying hundreds of passengers. However, no operational aircraft has any "protection" against the effects of volcanic ash - there is no requirement for jet engines to be certified to be able to cope with the ingestion of any amount of ash. Thus warning of the whereabouts of a volcanic ash cloud is, arguably, the most important function of any organisation charged with providing a range of warning services to transport aviation. The UK Met Office is responsible for providing SIGMETs ("forecasts" for up to 6 hours ahead) to aircraft in the Shanwick Oceanic Control Area (a map of which is given in section 2) including warnings of volcanic ash clouds. In addition we have responsibility for providing longer range forecasts of ash cloud movement in the whole of the North Atlantic area.

A somewhat anecodotal account of the effects of volcanic ash on aircraft is given in Steenblick (1991). Up to now, no aircraft has had to ditch in the sea due to complete engine failure following an encounter with a volcanic ash cloud. Hoyle (1991) hints at the likely sequence of subsequent events if an aircraft ditched in the sea near Iceland. If an incident involved multiple aircraft, the time taken to affect a rescue of all passengers, alive or otherwise, would be proportionately increased.

Air traffic in the North Atlantic has three noteworthy characteristics: it is

- High density. This is best expressed by the number of aircraft per day in each direction. At busy times this reaches 250, and average numbers increase steadily from year to year.
- Subject to a rather restricting communication, navigation and surveillance (CNS) regime. This essentially means that, rather than relatively spontaneous communication between controller and aircraft, communication generally occurs in a rather ordered way, and in the absence of any communication, a de facto flight plan can be followed by all aircraft without jeopardizing safety. It is useful to compare air traffic control in the North Atlantic with the domestic airspace scenario, where radar cover and line-of-sight communications are the norm. In the latter, the controllers have relatively up-to-date information on aircraft position, and can respond relatively quickly to a request for a change of routing, even if other aircraft have to be diverted as a consequence. It is worth commenting that the authors are not experts in air traffic control!
- Subject to meteorologically dependent routings. Tracks are defined for eastbound and westbound air traffic so that, essentially, tailwinds can be exploited and headwinds avoided.

Consequential on the above factors is the existence of the North Atlantic Organized Track System (NAOTS). Normally five or so tracks in each direction are identified which are close to optimum routes for a usefully large number of origin/destination pairs. These tracks are normally approximately parallel, usually with no gaps in between, and traffic is not allowed to follow routes which cross these tracks. The density of traffic on these tracks is very high, with aircraft sometimes separated (in time and altitude) by the minimum allowed, and the tracks themselves are horizontally separated by the minimum horizontal separation. Not all traffic uses the NAOTS tracks: for origin/destination pairs such that the optimum route is well away from NAOTS tracks, such a route will be followed, within the usual air traffic control constraints. We will refer to these tracks as random tracks.

As will be shown, the NAOTS tracks pass quite close to the south of Iceland, and as this is, broadly speaking, a volcanically active region, there is clearly a potential threat to aviation from an eruption on Iceland. In this study we address only the short term threat, that is the threat from an eruption to those aircraft already in flight. In practice this means looking at the events in the first 6 hours after an eruption, 6 hours being broadly the time taken to fly across the Atlantic. This is not to say that problems will not be posed to those aircraft taking off after the eruption. A working figure is that a volcanic ash plume more than 48 hours old does not pose a threat to aviation. However, approximately seven times as many flights will be affected by a plume between 6 and 48 hours old as will be affected by a plume in its first 6 hours. But because of the difficulties of providing a forecast in the first few hours after an eruption, and because of the CNS regime in the North Atlantic, it is considered that the short term threat is worthy of special attention. In particular, the threat to traffic on the NAOTS tracks is of special interest.

Various factors suggest that the short term threat to eastbound traffic is much greater than the threat to westbound traffic. These factors are:

- There is a shorter distance from UK domestic airspace to the area threatened by an Icelandic eruption than the distance from Canadian domestic airspace. Thus on average, at the time of an eruption, the majority of the westbound traffic would be either beyond the area at risk or within UK domestic airspace so that it could readily be diverted to a UK or Irish airfield.

- Windflow in the North Atlantic determines both the NAOTS tracks and the trajectory of the ash following an eruption. As will be shown, the effect of this is that, when the ash comes furthest south, the eastbound tracks are well north of their normal position.

- Eastbound air traffic is more highly concentrated than westbound. The extra concentration in time arises because of airport curfew constraints. The traffic is often more concentrated with respect to latitude so that jet streams can be exploited.

In fact it can be shown that, in the worst case of ash affecting the eastbound NAOTS tracks, none of the westbound tracks are affected. Thus this study will only address the problem for eastbound flights.

Section 2 of this report assesses the general probability of an eruption on Iceland of sufficient explosiveness to eject tephra (a collective term applied to all pyroclastic (literally, "fire-broken") particles or fragments ejected from a volcano, irrespective of size, shape or composition) to translatlantic flight levels. Section 3 gives examples of aircraft and volcanic ash trajectories, which illustrate the convergence that can occur both in extreme meteorological circumstances and in more average conditions. In section 4 we look at one extreme case and quantify the cost of avoiding the convergence. The likelyhood of the extreme case, and close approximations to it, is addresssed in section 5. Section 6 appraises the feasibility of using satellite data to monitor ash distribution and movement. A final section presents conclusions and recommendations.

2 A historical perspective of explosive eruptions on Iceland

Essentially we are interested in eruptions where there was evidence of tephra reaching transatlantic flight levels. There have been 4 of these in the last 50 years, all involving Mount Hekla, which is at 64^o north, 19.65^o west. In addition Askja erupted in 1961, and although the cloud for a short while reached about an altitude of 10km (33000 feet), the uppermost part of the cloud was thought to consist of vapour and gases. Therefore for the statistical calculations that follow Askja will be ignored. There have been a number of "minor" eruptions, most notably that which lead to the formation of Surtsey (1963-7), and these will also be ignored: it is not clear how safe this is, statistically.

The eruptions of Hekla are summarised in the following table.

Date	*time*	*cu m of tephra*	*Max height of cloud*	*Length of eruption*
29/3/47	0641	$180M$	$30km$	$80mins$
5/5/70	2123	$70M$	$16km$	$160mins$
17/8/80	1327	$60M$	$15km$	$120mins$
17/1/91	1700	$20M$	$12km$	$110mins$

The length of eruption figure is of necessity somewhat subjective. What is intended here is the length of time for which tephra were ejected to near tropopause levels: what frequently happens is that initially tephra is ejected to very high levels and gradually the level becomes lower. In the case of the 1947 eruption material was ejected for 14 months after the initial date, but only during the first 80 minutes were very high altitudes attained.

The reason for the duration figure is so that we can calculate order of magnitude probabilities of there being an eruption in progress at any time. We will take the order of magnitude of the length of eruption as 1 hour, and the separation of eruptions as 15 years. Hence the probability of an eruption at a particular time is equal to the reciprocal of the number of hours in 15 years, i.e. 10^{-5}.

The 1947 eruption is of particular interest, because it occured in a northerly airflow. As reported in Thorarinsson (1950), the ash initially moved southsouthwest, passing over a ship at 57^o north, 20^o west approximately 11 hours after the eruption. Thereafter the ash moved broadly eastwards, crossing Northern Ireland, Scotland, southern Norway, southern Sweden and giving rise to deposits in Finland. The ash was mainly between 500hPa and 300hPa. At that time air traffic was, by comparison with today, not of such high density, lower flying and predominantly propellor driven, so the threat was much smaller.

3 Examples of aircraft and volcanic ash trajectories

Figure 1 illustrates the convergence of the two types of trajectory in the first 6 hours after the eruption, for the night of 27th - 28th August 1994. The chart shows coastlines, lines of latitude and longitude every 30 degrees (dashed), the boundary of the Shanwick OCA (Oceanic Control Area) (dot-dashed), and the tracks of several aircraft crossing the North Atlantic. These were derived from reports of meteorological conditions made by those aircraft and sent to us at Bracknell. Thus they indicate a subset of the route used that night. Also shown are digits 0 thru 6 which indicate the very crude position of the southern extremity of the volcanic ash during the first 6 hours, asuming an erruption at 0000GMT from the southern tip of Iceland. This shows that several routes would be affected, and that the ash enters the Shanwick OCA approximately 4 1/2 hours after the eruption.

In this case the tracks affected are the random tracks; the NAOTS tracks are further south, pointing approximately to the bulge in the Shanwick OCA round Irish airpsace. Thus in this case the number of aircraft affected would be rather small, probably less than ten.

This particular case was chosen having been subjectively judged to be the worst possible case during the 20 days prior to 5th September 1994.

Figure 2 is directly analagous to figure 1, but for the 20th April 1994. This occasion is the worst case in

the two year period from 1st May 1992 to 30th April 1994. In this case the wind from Iceland is an almost straight northerly of over 100 knots. As mentioned in the introduction, this flow has two effects:

- The volcanic ash spreads much further south in the first 6 hours - in this case to south of 54 degrees.
- The NAOTS tracks are much further north than they usually are. This is deliberate so that the aircraft can pick up a very strong tailwind for the last portion of their flight. The NAOTS tracks are those whose eastern ends lie between the figures "3" and "6".

The combined effect of these two factors is that the ash affects essentially all the NAOTS tracks (although conceivably a very early flight on the southernmost track would be unaffected). Probably 100 or more aircraft would have been using the NAOTS tracks on this occasion.

4 Cost of pre-flight avoidance tactics

Although it is clearly desirable to have a fully developed and tested warning system, and even, conceivably, rehearsals of in-flight avoidance tactics, it is worth considering whether changes in flight planning could reduce risks without excessive extra costs. Therefore the flight time saved by using the optimum eastbound routes on 20th April 1994 was calculated. The set of 56 Europe/America city pairs used in Hunter et al (1988) was used in the calculation. It should be stressed that we were seeking the order of magnitude of the saving. Therefore we did not weight the city pairs by air traffic as should have been done in theory. Figure 3 shows the optimum routes for those pairs. These are the theoretical optimum routes - it is recognised that real routes, especially over land, are highly constrained by air traffic control considerations - but for the purposes of calculating the savings this approach is adequate. Also shown are a subset of the winds used in the calculation, which were for 250hPa (34000 feet) at 00Z on 20th. An airspeed of 500 knots was used in the calculation, which used the technique described in Lunnon and Ahmed (1993). Figure 4 shows the great circle routes. Whereas in figure 3 the core of routes (particlarly those to London and Frankfurt) is, at 30^o west, at about 60^o north, in figure 4 the core is at about 55^o. Thus it is argued that if, on this occasion, the NAOTS tracks were set on great circle considerations, they would be sufficiently far south for there to be no threat from volcanic ash. The average time saving for the 56 city pairs is less than eight minutes, and using the figures quoted in Lunnon and Ahmed (1993), this equates to a cost saving of £31,400.

The relatively small time, and cost, saving occurs for the following reason. Large time savings are obtained in essentially zonal flows, when a small change of route can enable a jet stream to be exploited. In the 20th April case, a large change of route is necessary to exploit the predominantly meridional circulation, so the time saving is small.

5 The probability of aircraft and volcanic ash trajectory scenarios

Clearly it is necessary to quantify the likelyhood of the 20th April scenario. The key figure is the meridional (north-south) component of wind at Iceland, which we can examine using radiosonde data. From the full ascent, including special points, the maximum meridional component for the part of the ascent between 500hPa and 100hPa was extracted. The statistical distribution of this parameter is shown in figure 5, again for the two year period from 1st May 1992 to 30th April 1994. The ten cases of strongest wind are individually listed in the following table.

Date	*maximum northerly wind (knots)*	*tropopause pressure (hPa)*	*vector shear (kn/hPa)*
21/9/92	78	230	1.00
24/9/92	82	260	0.39
13/5/93	80	185	0.47
14/5/93	84	221	0.55
15/5/93	91	301	0.11
22/8/93	82	222	0.80
16/1/94	70	224	0.18
19/4/94	110	249	0.14
20/4/94	100	198	0.60
22/4/94	76	278	0.30

As can be seen, the 20th April 1994 has the second highest northerly wind component. Diagrams analagous to figures 1 and 2 have been examined for all these cases, and only in that for 20th April are all NAOTS tracks affected by the ash. In most cases only one or two tracks are affected. It is concluded that a case such as 20th April 1994 occurs on average of the order of once per year. Combining this with the probability of an eruption at any time, it appears that the probability of the figure 2 scenario is approximately $3 * 10^{-8}$. While this is a small number, figures of 10^{-8} or 10^{-9} are frequently quoted as "acceptable" accident probability figures. Furthermore, of the order of 100 aircraft are nominally affected in the figure 2 scenario, so conventional accident statistics do not necessarily apply.

In order to assess the impact on random tracks, it was thought useful to present the probability statistics in cumulative form, and this is done in figure 6. This shows the probability of a particular northerly component being exceeded. Thus for example there would appear to be a 10% probability of a northerly component in excess of 30 knots. The probability of any northerly component (as opposed to a southerly component) is close to 50%.

The latitude of Hekla is 64^o, and the northernmost extent of the Shanwick OCA is 61^o. Thus the minimum distance is 180nm, which would require a wind component of 30 knots to be crossed in 6 hours. From figure 6, a wind component in excess of 30 knots has a probability of 10%. Combining this with the probability of an eruption gives a probability of 10^{-6} of an eruption occuring *and* the ash reaching the Shanwick OCA in under 6 hours.

6 The feasibility of using satellite data to monitor ash distribution and movement

It is clear that satellite data would have a primary role in ascertaining the position of the ash cloud at all times while it remained a threat to aviation. It was thought worthwhile to do some preliminary calculations as to how easy it would be to use satellite data in the context of providing rapid forecast information following an eruption on Iceland. Both polar orbiters and geostationaries could be used: the advantage of polar orbiters is greater detail: a capability to distinguish ash clouds from hydrometeor clouds, and a limited capability to ascertain the height distribution of the ash even when overlaid by hydrometeor clouds. The advantage of the geostationary is almost continuous coverage in time. A key question therefore is whether the aircraft would be flying in the troposphere or the stratosphere, assuming that there is no cloud in the stratosphere. In table 1 the tropopause pressure is listed for the 10 cases of strongest wind component: the mean of these values is 236hPa (approximately 35000 feet). Examination of the aircraft data shows that, for these ten cases, at 00Z, the majority of aircraft were at 35000 feet or higher. As the aircraft moved eastwards into the Shanwick OCA they would be likely to request a higher flight level, to obtain optimum performance (descent would start somewhat later in the flight). Thus it appears that for these cases the vast majority of aircraft would, at the

critical stage of the flight, be flying in the stratosphere. Note though that the mean tropopause pressure at Iceland for the entire two year period is 278hPa (approximately 32000 feet) so flying in the stratosphere when over Iceland is the normal occurence.

From geostationary imagery at a particular time it will be rather difficult to ascertain the height distribution of the ash cloud. However, the most promising approach using geostationary imagery is to track the cloud between consecutive images, obtain a motion vector and by comparison with a known wind field obtain the height. The methodology for obtaining this empirical level of best fit (ELBF) was defined in Lunnon et al (1992). A critical issue is the amount of wind shear, and in table 1 we show the vector wind shear between the two levels which span the tropopause. The reason for looking at the shear at this level is because an essential question to be answered is whether there is any ash in the stratosphere - in view of the altitude of aircraft this is the overiding issue. The average value of the vector wind shear for the 10 cases is 0.45 knots/hPa, whereas the average value for the two year period is 0.23 knots/hPa. Although in the case of 15th May 1993 the wind shear across the tropopause is only 0.11 knots/hPa, in this case the tropopause was at 301 hPa (approximately 30000 feet), and the shear at levels where the aircraft were flying was much greater. Thus it appears that in most of the cases when an eruption would pose a threat, the wind shear is adequate to discriminate between a purely tropospheric ash cloud and one that has penetrated the tropopause.

Although the foregoing implies that good use can be made of geostationary data, a careful examination should be made of the use of polar orbiter data. If there is some choice in the matter, then the best time to issue a SIGMET would probably be shortly after a polar orbiter overpass over the area in question. Timings of orbits should be examined to see if this is acceptable to the users.

It is worth pointing out that the height of an ash cloud from Mount Hekla can, in the early stages, be monitored by radar from Keflavik airport. However, considerable uncertainty exists as to the height reached by several of the eruptions from Hekla. Furthermore volcanoes in the north east part of Iceland cannot be monitored in this way. Thus while some information would be available from radar, the use of satellite data should be regarded as essential.

7 Conclusions and recommendations

The probability of an eruption occuring *and* the ash reaching the Shanwick OCA in under 6 hours, at 10^{-6}, is rather high, given the uncertainty as to how accurate a SIGMET would be and how quickly it could be issued. The probability of an eruption occuring *and* the ash reaching all the NAOTS tracks in under 6 hours, at $3 * 10^{-8}$, is obviously lower but the problems of dealing with this situation are much greater, as is the number of aircraft potentially affected.

Although it is clear that satellite data has the potential to allow an expeditious warning to be made, some research, development and, with most difficulty, testing, would be needed before operational implementation. The following "stopgap" arrangement is proposed. When the NAOTS tracks are set, a check is performed as to whether an eruption on Iceland subsequent to the takeoff of aircraft would affect the tracks. If so, the tracks are moved further south until there is no risk. As shown, the scenario illustrated in figure 2 occurs only of the order of once a year, and the cost in extra fuel, $\sim$£30K, is rather small. Another possibility would be to take the tracks to the north of Iceland, but it is believed that that would be more expensive.

It has been pointed out to the writer that the effect of volcanic ash on a jet engine is much reduced if the aircraft is flown at lower mach number. While this would have ramifications for the amount of fuel required to reach the destination, the imposition of a speed limit on the NAOTS tracks in the event of an eruption is another "stopgap" solution which should be investigated further.

It has been suggested that an artificial eruption should be staged for training purposes. This suggestion is endorsed, although a practical working definition of such an eruption will need to be developed. Alternatively, tests of the individual components of the warning and avoidance "chain" should be performed.

8 Acknowledgements

Unnur Olafsdottir, of the Icelandic Meteorological Office, and Gudrun Larsen, of the University of Iceland, have both provided material presented here, which is gratefully acknowledged.

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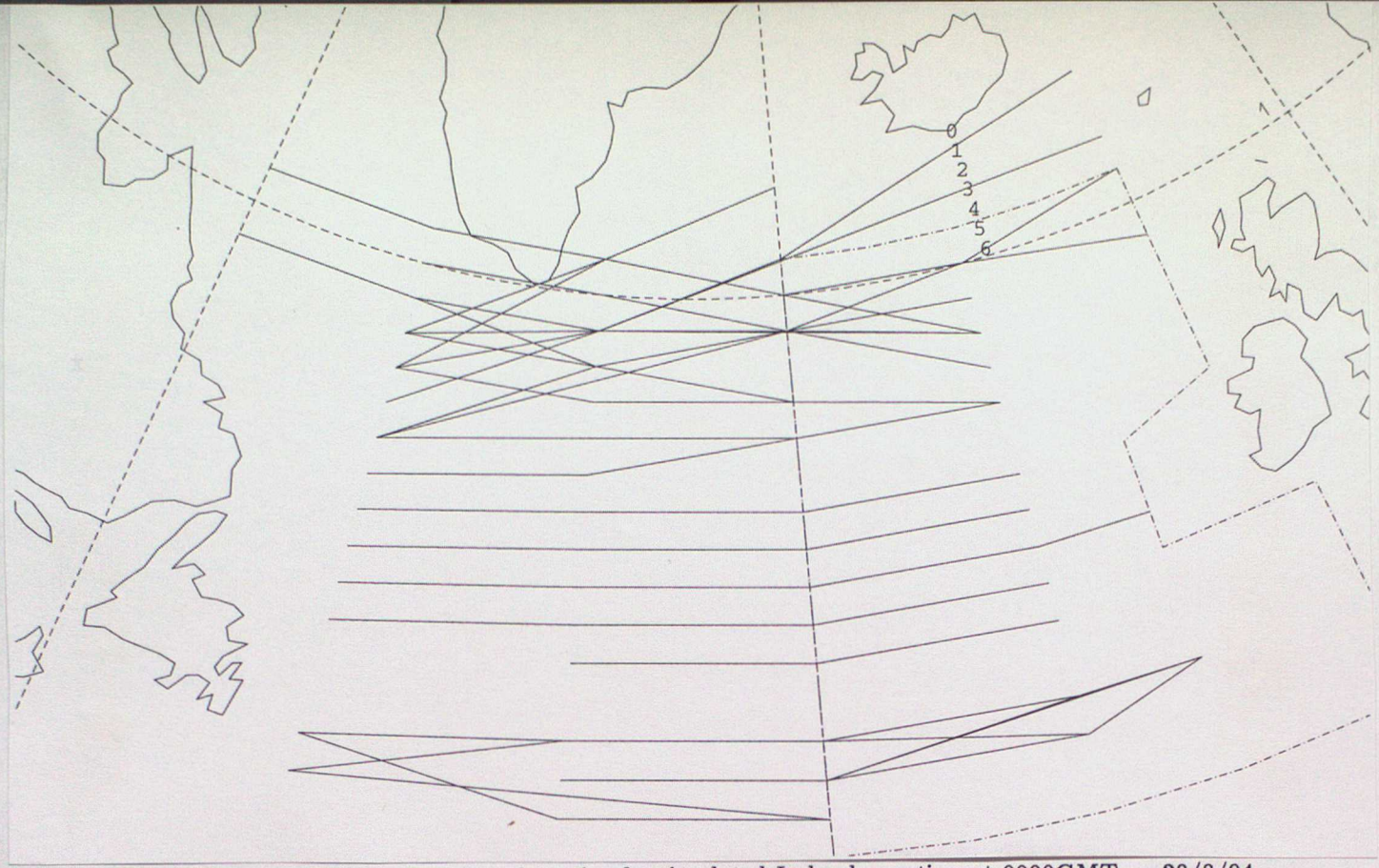

Figure 1. Aircraft and volcanic ash trajectories for simulated Iceland eruption at 0000GMT on 28/8/94

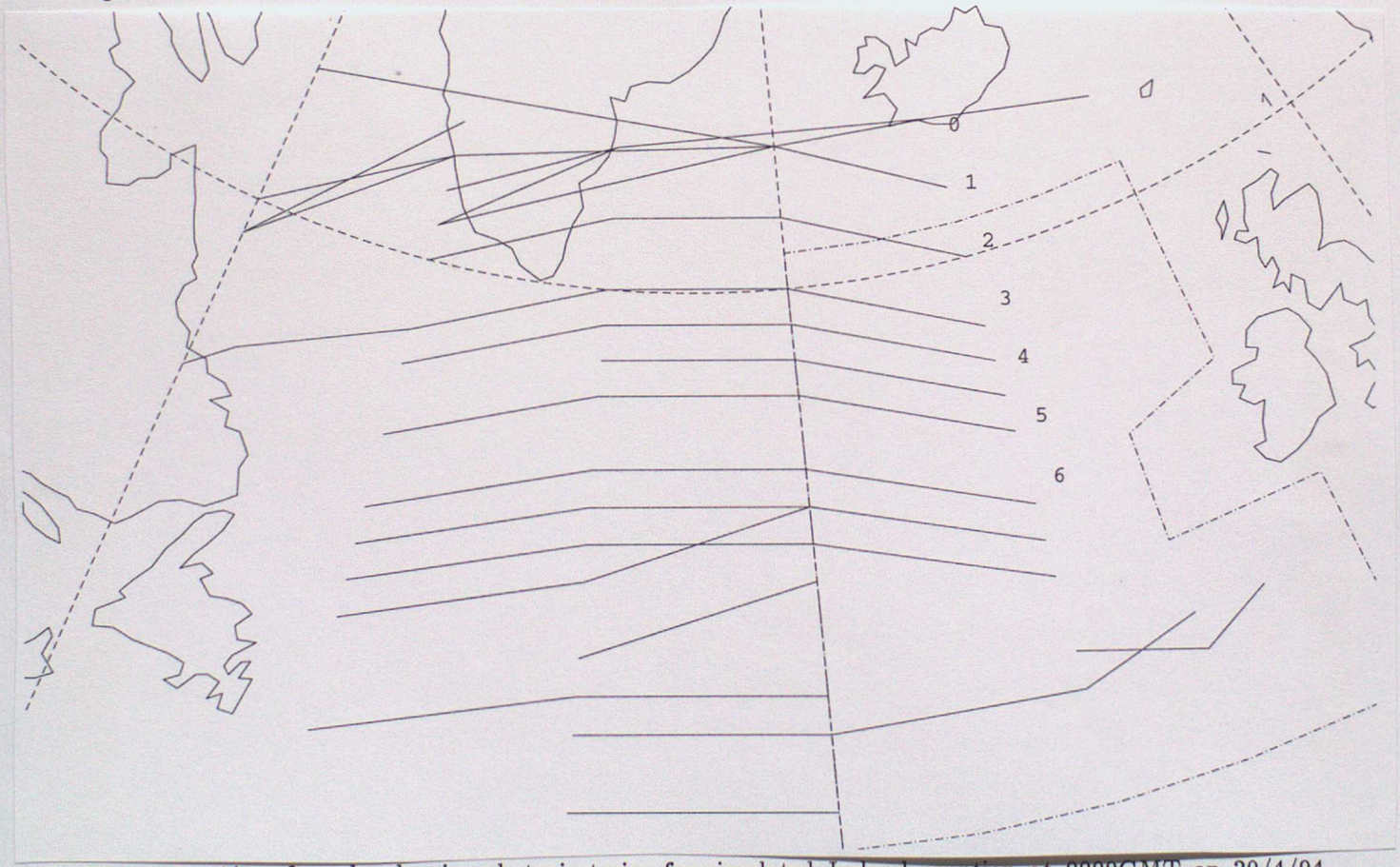

Figure 2. Aircraft and volcanic ash trajectories for simulated Iceland eruption at 0000GMT on 20/4/94

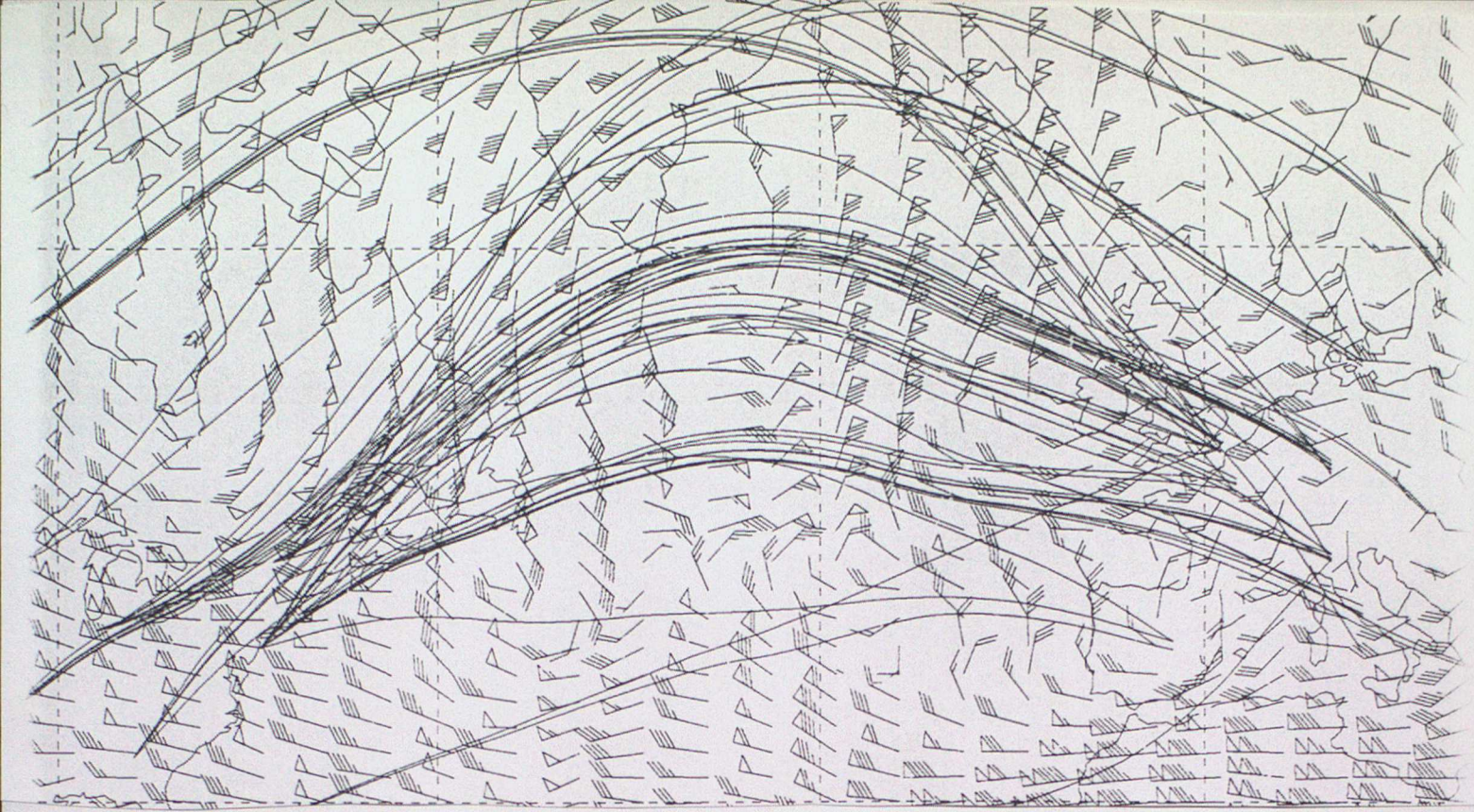

Figure 3. Optimum eastbound routes for 56 city pairs for 20th April 1994

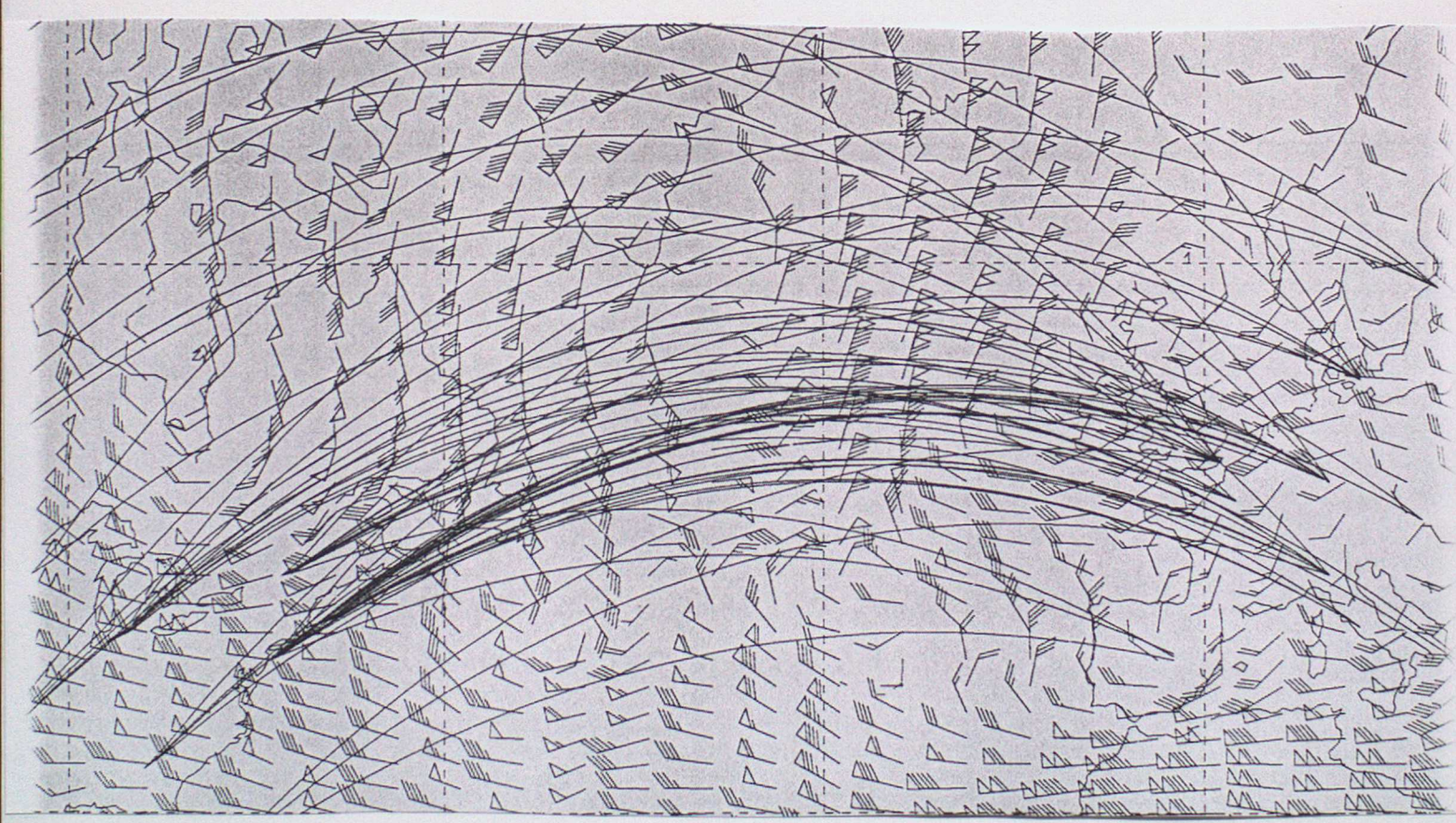

Figure 4. Great circle routes for 56 city pairs

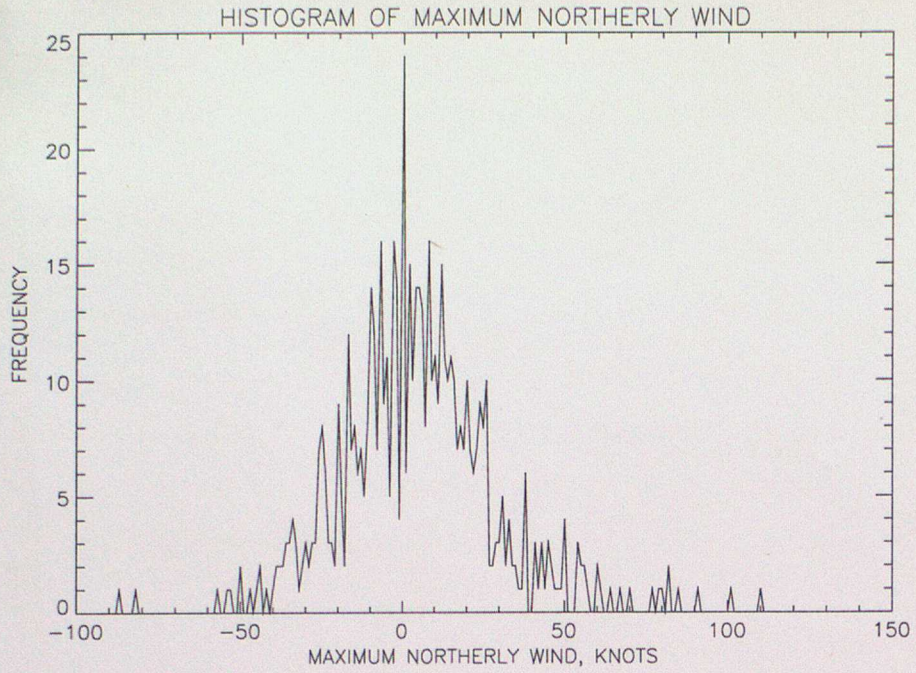

Figure 5. Statistical distribution of maximum meridional component

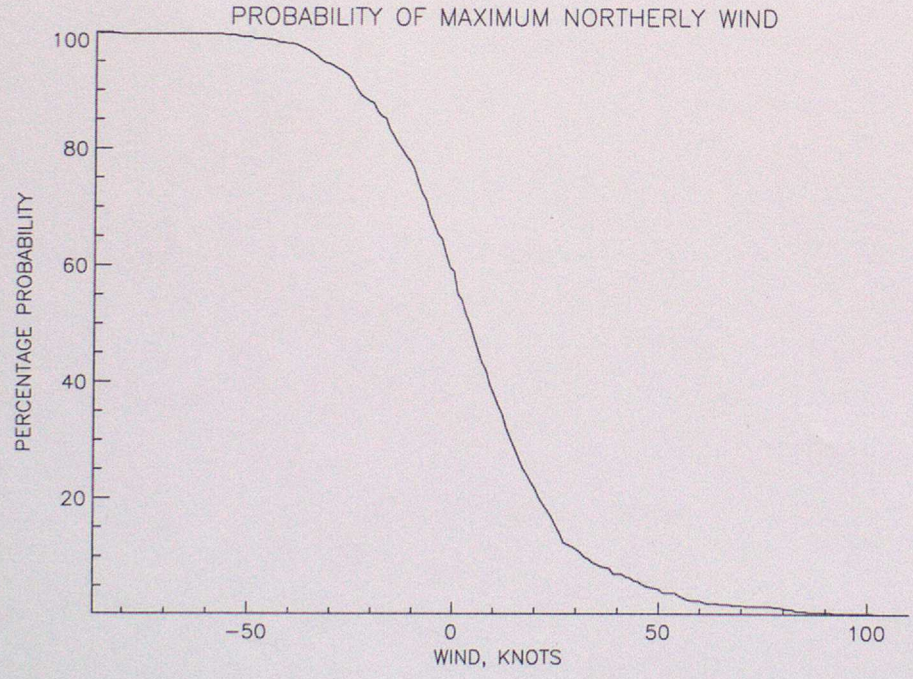

Figure 6. Cumulative probabilities of maximum meridional component